Concurrent Performance of Stroop and Single-Leg Balance Influences Postural Control Under a Dual-Task Paradigm

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Abstract

Though clinical assessments incorporate single-task (ST) paradigms, daily activities integrate cognitive and motor tasks concurrently rather than independently. Therefore, dual-task (DT) paradigms may better reflect overall performance. The purpose of this study was to determine if differences in cognitive and motor performance existed between ST and DT paradigms with two Stroop variations. Eighteen healthy college students (four males, 20.78±1.06 yrs., 168.49±9.10 cm, 63.88±7.90 kg) volunteered. Participants performed two Stroop variations: 1) $Stroop_{single}$: one color-word stimulus presented every two seconds for 48 seconds and 2) $Stroop_{multiple}$: 24 color-word stimuli presented simultaneously. The cognitive (Stroop) and motor (single-leg balance) assessments were performed under ST (independently) and DT (concurrently) paradigms on a tri-axial force plate. Participants verbalized the color of the color-word while maintaining postural control. Center of pressure (CoP) speed (cm/s) and time-normalized 95% elliptical sway area (cm^2/s) were calculated to quantify postural control. The number of correct congruent and incongruent responses of Stroop were recorded to quantify cognitive performance. Repeated measures one-way ANOVAs were performed for each outcome variable with alpha level set *a priori* at $p \leq 0.05$. No differences in cognitive performance were observed between ST and DT for both Stroop assessments ($p > 0.05$). CoP speed was slower under both DT assessments than under ST ($p < 0.01$). With $Stroop_{multiple}$, total sway speed ($p < 0.01$) and sway area ($p < 0.01$) differed under DT compared to ST. Higher postural control variation under DT may require greater attention for Stroop than single-leg balance. Clinicians should consider incorporating DT paradigms to comprehensively assess cognitive and motor performance, as this would aid clinicians in return-to-play decisions and assessing injury.

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Chapter 1: Introduction

1.1. Rationale

Single-task (ST) cognitive and motor assessments play an important role in identifying deficiencies and evaluating performance following sport-related injuries, such as concussions (Broglio, Sosnoff, & Ferrara, 2009; Sosnoff, Broglio, & Ferrara, 2008; Cavannaugh et al., 2005; Guskiewicz, 2003; Schmidt, Register-Mihalik, Mihalik, Kerr, & Guskiewicz, 2012; Ingriselli et al., 2014; Talarico et al., 2017) and ankle sprains (Ross, Guskiewicz, Gross, & Yu, 2009; Arnold, De La Motte, Linens, & Ross, 2009; Perrin PP, Béné , Perrin CA, & Durupt, 1997; Czajka, Tran, & Cai, 2014; Chen CY, Hsu, Guo, Lin, & Chen YA, 2011). By identifying performance discrepancies between healthy and injured individuals, clinicians are able to make reasonable judgments to guide return-to-play decisions and injury management. However, a ST paradigm might not accurately reflect the dynamic nature of physical activities and everyday tasks. Often multiple tasks are performed concurrently and rarely in isolation of each other (Plummer & Eskes, 2015; Tsang, Chan, Wong, Yip, & Lu, 2016; Ingriselli et al., 2014). Therefore, it is crucial that clinical assessments used to evaluate performance of athletes accurately reflect the dynamic environment in which they train and compete. A dual-task (DT) paradigm is one way to test an athlete's response to a dynamic environment by testing a motor component and a cognitive component simultaneously. A single-task paradigm therefore is testing the cognitive and motor component independently. This study aimed to compare cognitive and motor performance of healthy active college students under ST and DT paradigms when completing two variations of a Stroop test.

1.2. Introduction

Two domains commonly affected by sports-related injuries are motor and cognitive performance (Broglio & Puetz, 2008; Catena, van Donkelaar, & Chou, 2009; Moser et al., 2007). The ability to attain and maintain body position, more specifically balance, is critical when performing or learning motor skills (DiNucci, 1976). Since most sports require a high-level of balance skills that integrate multiple sensory inputs, it is important to perform a comprehensive assessment of postural control following sports-related injuries to evaluate and manage the injury (Massingale et al., 2018). By incorporating a DT paradigm into injury evaluation, clinicians can comprehensively assess performance deficiencies and create targeted treatment plans for every athlete (Massingale et al., 2018, Howell, Osterning, & Chou, 2013; Sosnoff et al., 2008; Teel, Register-Mihalik, Blackburn, & Guskiewicz, 2013; Register-Mihalik, Littleton, & Guskiewicz, 2013; Ross et al., 2009).

Static postural control is often assessed when a clinician is evaluating and managing an injury. By attempting to keep a stable base of support without intending to move (Arnold et al., 2009; DiNucci, 1976), the visual, somatosensory and vestibular inputs of static postural control are being challenged (Blaszczyk & Michalski, 2006). To assess static postural control, it is important to implement paradigms that tests each sensory input that contributes to the postural control system. Static postural control assessments, such as single-leg balance, help provide the information needed for clinicians to offer the best care and to make good, reliable and safe return-to-play decisions (Guskiewicz, Ross, & Marshall, 2001; Brachman et al., 2017).

In addition to postural control, cognition is also assessed when clinicians are evaluating and assessing sports-related injuries. One such cognitive evaluation is the Stroop color-naming task, which is well suited for evaluating flexibility in the control of cognitive processes and behavior (Bugg, Jacoby, & Toth, 2008). Though Stroop tests can vary in stimuli quantity, size and presentation, implementation, and scoring methods (Bayard, Erkes, & Moroni, 2011), the additional time taken to name the ink color in an incongruent relative to a congruent condition is still noted as Stroop Interference (Bugg et al., 2008). This effect has been reported in individuals with Parkinson's (Djamshidian, O'Sullivan, Lees, & Averbeck, 2011), Alzheimer's (Bayard et al., 2011), Attention Deficit Hyperactivity Disorder (Schwartz & Verhaeghen, 2008), Schitzophrenia and Obsessive-Compulsive Disorder (Lee, Shin, & Sunwoo, 2009), and concussion (Howell et al., 2013).

With this understanding, clinicians are able to test athletes shortly after a suspected injury since an increase in dual-task cost or a decrease in cognitive accuracy is reported at a minimum of 72 hours post-injury (Howell et al., 2013; Howell, Osternig, & Chou, 2014; Howell, Osternig, Koester, & Chou, 2014). Similarly, clinicians are able to monitor progress or clear for return-to-play by using DT paradigms compared to the traditional use of ST paradigms (Catena, van Donkelaar, & Chou, 2007a; Catena, van Donkelaar, & Chou, 2007b; Catena et al., 2009). Therefore, DT paradigms using the Stroop test prove beneficial in probing how an individual will perform when engaging in the regular activities of daily living during recovery (Howell et al., 2013).

1.3. Purpose

The purpose of this study was to determine if differences in cognitive and motor performance existed between ST and DT paradigms when performing two variations of Stroop.

1.4. Research Questions and Hypotheses

Research Question 1: What are the differences in cognitive performance between ST and DT in a healthy population?

Hypothesis 1: Participants will have fewer correct congruent and incongruent responses under DT than ST for both variations of Stroop.

Research Question 2: What are the differences in motor performance between ST and DT in a healthy population?

Hypothesis 2.1: Participants will display a slower total speed under ST than under DT.

Hypothesis 2.2: Participants will display a slower antero-posterior speed under ST than under DT

Hypothesis 2.2: Participants will display a larger RMS under ST than under DT.

Hypothesis 2.3: Participants will display a slower medio-lateral speed under ST than under DT.

Hypothesis 2.4: Participants will display a smaller sway area under ST than under DT.

1.5. Clinical Significance

Cognitive and motor assessments performed under a DT paradigm should be implemented to assess the recovery of an athlete following injury (Broglio, Tomporowski, & Ferrara, 2005). However, this is only applicable when the clinician has a baseline for that athlete to assess deviations from that individual's performance when healthy. Static postural control assessments help provide the information needed for clinicians to offer the best care and to make good, reliable and safe return-to-play decisions (Guskiewicz et al., 2001; Guskiewicz & Broglio, 2011). Selective attention tests are accurate (Franzen, Tishelman, Sharp, & Friedman, 1978) and valuable assessments when used to identify disease or recovery from injury. Combining a cognitive component with a motor component under a DT paradigm is thought to better represent human multitasking because of the simultaneous processing of information across multiple cognitive domains required in sports (Broglio et al., 2005; Parker, Osternig, van Donkelaar, &

Chou, 2008; Ingriselli et al., 2014). Incorporating DT evaluations into athletics assessments could provide a more comprehensive assessment of an athlete's performance while on the sidelines or in the clinic for suspected injury. Clinicians are also able to monitor progress and make return-to-play decisions by using DT paradigms compared to the traditional use of ST paradigms (Catena et al., 2009, Catena et al., 2007a; Catena et al., 2007b). Therefore, DT paradigms yield insight about an athlete's injury progression when comparing to their normative or healthy performance and aid the clinician in clearing the athlete for activity.

Chapter 2: Review of the Literature

2.1. Selective Attention

2.1.1. Definition

Humans especially rely on selective attention daily in order to function as efficiently and as resourcefully as possible. Selective attention is described as the differential processing of simultaneous sources of information (Johnston & Dark, 1986), or the method in which the brain is dominated by one entity over another (Driver, 1998). By focusing on another stimuli or task, one could neglect visual objects or words spoken (Driver, 1998). But devoting one's attention to a single stimulus or a select group of stimuli is not necessarily considered problematic. Being able to utilize selective attention can enhance performance or retention of stimuli while quieting unnecessary background noise (Bee & Micheyl, 2008). Selective attention is a means by which the cognitive processing can dictate what is most important so as not to overwhelm attentional resources by inferior information (Driver, 1998; Lavie, 2000).

2.1.2. Theories of Selective Attention

There are two main types of selective attention theories: auditory and visual. Prior to the 1950s, theories of auditory selective attention have focused on the "cocktail party" theory (Bee & Micheyl, 2008). The nomenclature of this theory explains why someone can hear another person talking to him or her amid a crowded room (Bee & Micheyl, 2008). With increased sound interference in a signal detection threshold, a decrease in the ability to discriminate other signals of lesser importance is observed (Ehret & Gerhardt, 1980; Gerhardt & Klump, 1988; Langermann, Gauger & Klump, 1998; Lohr, Wright & Dooling, 2003; Schwartz & Gerhardt, 1995; Wollerman, 1999; Wollerman & Wiley, 2002).

Broadbent et al. (1958) proposed a visual model of selective attention which incorporated two main questions: 1) what are the differences in inputs or stimuli needed for selective attention to occur and 2) what does the person know about the input? In other words, it is important to consider the similarity of the tasks as well as the knowledge the participant has about the tasks. If cued to focus on particular visual stimuli, the individual will possess a better memory for the stimuli compared to an individual who was not given specific instructions (Broadbent, 1958). This investigation proves not only how crucial the surrounding stimuli are but also the instruction or prior knowledge of the individual.

A later theory of selective attention was focused around the work of Rock and Gutman (1981) who argued that poor memory reflected an absence of perpetual processing when presented with a task. This study incorporated certain shapes and colors where the participants were instructed to focus on the shapes in one color only (Rock & Gutman, 1981). When asked about the shapes in the specified color, the participants displayed a good memory for attended shapes, but failed to remember the number or quantity of familiar shapes (Rock & Gutman, 1981). Since the participant was only able to recall information that they were instructed to report, this study further illustrated the idea of Broadbent's theory and its application to the visual memory for shapes and colors. In a different light, this instance illustrates that information is not retained unless prompted to retain it, dismissing all other input.

2.2. Stroop Assessments

The Stroop paradigm evaluates susceptibility to interference and has proven to be sensitive to dysfunction in frontal lobes and drug effects (Pilli, Naidu, Pingali, Shobha, & Reddy, 2013; Harvey, Clayton, & Betts, 1978; Foreman, Barraclough, Moore, & Mehta, 1989; Hasenfratz & Battig, 1992; Parrott & Wesnes, 1987; Wesnes & Warburton, 1984; Desager et al., 1988; Boulenger et al., 1989; Griffiths, Jones, & Richens, 1986; Jensen & Rohwer, 1966; Provost & Woodward, 1991; Mair & McEntee, 1986; Kenemans, Wieleman, Zeegers, & Verbaten, 1999; Patat et al., 2000; Edwards, Brice, Craig, & Penri-Jones, 1996). One type of assessment is a Stroop Color-Word Test (SCWT) that evaluates an individual's selective attention and cognitive flexibility (Strauss & Spreen, 1998). This assessment relies on discontinuity between color and word pairings. Depending on the experimenter, the participant is asked to verbalize either the color of the word or the word itself. The ability to follow instructions as well as responding correctly are being tested. The formats of these assessments vary; however, the two most common formats are one color-word stimulus per presentation or multiple color-word pairings per presentation (Scarpina & Tagini, 2017).

The first stage of the protocol acts as a control for the participant, where he or she is instructed to verbalize the color of a picture shown on a computer monitor. During the second stage color-words are presented which may or may not be in the same font color as the color-word. Responses typed in the font of the word's association were referred to as consonants, meaning that when the color of the font did not reflect the word itself were referred to as non-consonants (Afsaneh, Mojtaba, & Mehdi, 2012). Researchers believed that the second stage of the SCWT measured mental flexibility as well as the response to interference when subtracting the correct number of non-consonant score from the correct number of consonant score (Afsaneh et al., 2012). Although it was previously predicted that age, sex, or educational background would account for the variability in participant's selective attention (Moering, 2004; Wright & Wanley, 2003; Jerger et al., 1993; Van Boxtel, Ten Tusscher, Metsemakers, Willems, & Jolles, 2001; Hameleers et al., 2000), selective attention and cognitive level of an individual are affected more so by environmental factors, such as disease (Afsaneh et al., 2012), or more specifically

Parkinson's (Djamshidian et al., 2011), Alzheimer's (Bayard et al., 2011), Attention Deficit Hyperactivity Disorder (Schwartz, 2008), Schizophrenia and Obsessive-Compulsive Disorder (Lee et al., 2009). Therefore, selective attention tests such as the SCWT are accurate (Franzen et al., 1978) and valuable assessments when used to identify disease or recovery from injury.

2.3. Static Postural Control

2.3.1. Definition

Static postural control, or the balancing on a stable surface without any intentional movement (Arnold et al., 2009; DiNucci, 1976), is considered an important aspect in learning or performing motor tasks (DiNucci, 1976). Static balance integrates feedback from the somatosensory, visual, and vestibular systems in order to reach steadiness (Johnansson & Magusson, 1991; Goldie, Bach, & Evans, 1989; Nashner & McCollum, 1985). Adequate postural control is needed to maintain upright stance and mobility for stabilization from voluntary arm and head movements (Johansson & Magusson, 1991; Dietz, 1992, Johansson, 1993; Magnus, 1924), hip movements (Nashner & McCllum, 1985), and ankle movements (Docherty, Valovich McLeod, & Shultz, 2006; Freeman, 1965; Hertel & Olmstead-Kramer, 2007; Konradsen & Rayn, 1991; Troop 1986, Troop, Odenrick, & Gillquist, 1985) necessary for activities of daily living.

2.3.2. Integration of Sensory System Information

To regulate postural control, a triple-input system of somatosensory (i.e. proprioception), vision, and vestibular sensory information and a single motor output of center of gravity are employed (Blaszczyk & Michalski, 2006); therefore, postural control is influenced not by one system but by three systems working in unison. If one or more of these systems are disturbed or influenced, postural control deficiencies could occur (Blaszczyk & Michalski, 2006).

The somatosensory system detects where body parts are in relation to the environment via the input of proprioceptors. Various proprioceptive organs and receptors incorporate afferent and efferent signals in order to maintain stability and orientation during quiet stance or movement (Bunton, Pitney, Cappaert, & Kane, 1993). Specialized neurons that transmit mechanical information about joint rotation and position into electrical signals are called mechanoreceptors (Grigg, 1986). When mechanoreceptors undergo trauma or injury, one can be susceptible to proprioceptive deficits, possibly leading to re-injury (Ergen & Bülent, 2008).

Vision is another key component to static postural control, especially peripheral vision. When incorporating peripheral vision in postural control assessments, participants display a smaller postural sway than the central vision field when focusing on a computer display with varied fields of vision (Berensci, Ishihara, & Imanaka, 2005). These findings demonstrate that peripheral rather than central vision contributes to maintaining a stable standing posture (Berensci et al., 2005). Keeping an open field of vision proves to be an important component to any athletic postural control testing. When administering a postural control exam, it is important to ensure that the participant's environment allows for an open field of vision to minimize extraneous variables.

The vestibular system is responsible for incorporating input from multiple sources to maintain postural control. The inner ear contains fluid filled organs called semicircular canals that are responsible for relaying information to the brain. Individuals display decreased postural stability and increased excessive movement with increased fluid flow through the semicircular canals (Jamon, 2014). The vestibular system plays a key role in regulating body sway as well as compensating for small, destabilizing impulses that the individual encounters (Horstmann & Dietz, 1988).

The integration of all three sensory inputs is crucial in determining postural orientation, or the active alignment of the trunk and head with respect to gravity, support surfaces, the visual surroundings and internal references (Horak & Nashner, 1986). With any complex integration of subsystems, many factors could potentially affect the postural control system and lead to an increased risk of injury (Schilling et al., 2009). Perturbations to the postural control system can be due to health or medical conditions such as diabetes (Simoneau, Ulbrecht, Derr, Becker, & Cavanagh, 1994), peripheral neuropathy (Simoneau et al., 1994), stroke (Schilling et al., 2009), multiple sclerosis (Corradini, 1997), Parkinson's disease (Rocchi, Chiari, Cappello, & Korak, 2006), cerebral palsy (Harris, Riedel, Matesi, & Smith, 1993; Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008), obesity (Corbeil, Simoneau, Rancourt, Tremblay, & Teasdale, 2001; Owusu et al., 1998), and concussion (Guskiewicz et al., 2001; McCrea et al., 2003; Riemann & Guskiewicz, 2000). By integrating somatosensory, visual and vestibular inputs, the postural control system is able to cohesively produce a center of gravity output to maintain balance.

2.3.3. Clinical and Laboratory Assessment

Clinicians assess static postural control to 1) determine where performance improvements can be made to increase everyday performance or athletic performance and 2) evaluate balance performance following an injury or progression towards recovery from an injury. The assessments used to measure static balance can be completed with or without instrumented balance testing devices.

Postural control can be assessed by incorporating single, double or tandem stance with variable conditions such as a firm surface, unstable surface, and eyes open or closed. A double-legged stance provides the widest base of support compared to single and tandem stance

(Palmieri, Ingersoll, Stone, & Krause 2002). Without any alterations in stance, the body is naturally challenged to maintain balance under normal stance conditions because two thirds of weight is balanced above ground over both of legs (Winter, 1995). Therefore, incorporating a single-leg or tandem stance pose an additional challenge to the postural control system. Single-legged balance is more demanding than double-legged stance due to the reduced base of support which requires the postural control system to make more adjustments in order to prevent a fall (Palmieri et al., 2002). When trying to place additional demands on the postural control system, a tandem stance, i.e. heel-to-toe stance, allows for an individual to keep the position longer than a single-legged stance since muscle fatigue often occurs in single-legged stance (Palmieri et al., 2002). Longer postural control trials allow clinicians to look at the effects of longevity that a narrowed base of support presents on performance. Compared to an eyes open and firm base of support scenario, individuals standing on foam with eyes closed display greater postural sway (Gill et al., 2001; Weirich, Bemben DA, & Bemben MG, 2010). The absence of visual input is thought to increase postural sway increases (Lanska & Goetz, 2000). Individuals with impaired balance naturally increase the use of their visual system as a way to compensate for the failure of another sensory input (Yelnik et al., 2015). This visual compensatory strategy leads to a visual dependence behavior, or the priority a subject gives to the visual input over balance control (Isableu, Ohlman, Cremieux, & Amblard, 1997; Bonan et al., 2004).

Postural sway may also increase when standing on an unstable or uneven surface where the somatosensory system is challenged to a greater extent than on a stable or firm surface (Nurse, Hulligerb, Wakelinga, Nigga, & Stefanyshyn, 2005). Mechanoreceptors on the soles of feet are important sources of afferent information required to regulate postural control (Magnusson et al., 1990) because they provide more information about surface contract pressures that are important for sensing small, continuous changes in posture (Vallbo & Johansson, 1984; Patel, Fransson, Lush, & Gomez, 2008).

Introducing balance perturbation into a postural control assessment aims to increase the demands on the postural control system with the intent of extracting residual deficits from balance disorders (Patel et al., 2008). A combination of decreasing visual input and balancing on an unstable surface tend to increase postural sway and highlight challenges to the postural control system that can be mitigated.

Considered the gold standard of balance testing (Goldie et al., 1989), instrumented testing devices such as the NeuroCom Smart Balance System uses the Sensory Organization Test (SOT) to measure the vertical ground reaction forces produced by a body's center of gravity (Bell, Guskiewicz, Clark, & Padua, 2011). During the SOT, conflicting information is delivered to the patient's eyes through visual disturbances and feet and joints through a swaying platform. The goal of the assessment is to disrupt afferent sensory information by reducing spatial awareness cues with somatosensory or visual components (Guskiewicz et al., 2001). The vestibular, visual and somatosensory systems are analyzed independently from one another in order to individually assess one component of balance. Overall, SOT presents a moderate level of reliability in a healthy population (Murray, Salvatore, Powell, & Reed-Jones, 2014) and normative SOT scores have been established for children (Foudriat, Di Fabio, & Anderson, 1993), the elderly (Pierchala, Lachowska, Morawski, Niemczyk, 2012), patients with vestibular disorders (Pedalini, Cruz, Bittar, Lorenzi, & Grasel, 2009), and the military (Pletcher et al., 2017).

If a clinician does not have access to a force plate or other laboratory methods of data collection, the Balance Error Scoring System (BESS) is commonly used to assess postural control (Bell et al., 2011). This assessment is comprised of three stages: a double-leg stance with hands on hips and feet together, a single-leg stance on the non-dominant leg with hands on hips, and finally a tandem stance where the non-dominant foot is behind the dominant foot (Reimann & Guskiewicz, 2000; Bell et al., 2011). The BESS is scored by counting the number of errors the participant makes such as lifting hands off hips, stepping to the side, falling, lifting heel, or abducting the hip more than 30° (Reimann & Guskiewicz, 2000; Bell et al., 2011). The BESS has proven to be a valid method in identifying balance deficits or concussed individuals compared to a healthy cohort (Guskiewicz et al., 2001; McCrea et al., 2003; Riemann & Guskiewicz, 2000). The BESS has also been used to assess time until lower extremity muscle fatigue (Erkmen, Takin, Kaplan, Saniolu, 2009; Fox, Mihalik, Blackburn, Battaglini, & Guskiewicz, 2008; Susco, Valovich McLeod, Gansneder, & Shultz, 2004; Wilkins, McLeod, Perrin, & Gansneder, 2004) as well as effects of ankle instability (Cornwall & Murrell, 1991; Friden, Zätterström, Lindstrand, & Moritz, 1989; Ross, Guskiewicz, Yu, 2005; Troop, Odenrick, & Giilquist, 1985). Single-leg, tandem stance, and unstable surface protocols help provide the evidence needed for clinicians to offer the best care and to make good, reliable and safe return-to-play decisions (Guskiewicz et al., 2001; Guskiewicz & Broglio, 2011).

2.3.4. Athletic Interventions

Exercises that incorporate single-leg balance or other static balance assessment are crucial for an athlete's return-to-play (Talarico et al., 2017; Brachman et al., 2017; Alsalaheen et al., 2013; Ménétrey, Putman, & Gard, 2014; Logan, O'Brien, LaPrade, 2016; Eitzen, Moksnes, Snyder-Mackler, & Risberg, 2010). In addition to assessing performance following injury, static postural control assessments can be used to determine points of weakness in the postural control system, which could lead to further injury in the future. Aside from assessing injury, static postural control training has been implemented into athletic practice with the goal of optimizing performance. Because each sport involves specific motor skills that require the completion of athletic-related movements and posture (Hrysomallis, McLaughlin, & Goodman, 2006; Maurer, Mergner, & Peterka, 2006; Paillard, 2017), balance is an important factor in the athletic environment (Brachman et al., 2017). Numerous balance surfaces have been reported effective in improving static and dynamic balance (Brachman et al., 2017) because of the added challenge to the postural control on stable and unstable surfaces in the antero-posterior and medio-lateral directions with or without recurrent destabilization (Cumps, Verhagen, & Meeusen, 2007; DiSefano, Clark, Padua, 2009; Hübscher et al., 2010; McHugh, Tyler, Mirabella, Mullaney, & Nicholas, 2007; Paillard, 2017; Söderman, Werner, Pietilä, Engström, & Alfredson, 2000; Verhagen et al., 2002; Zech et al., 2010). Improving balance of athletes by incorporating balance training into warm-ups has proven to elicit positive effects (Hrysomallis, 2007) on the reduction of sprains, dislocations, and ligament ruptures of knees, ankles, elbow, and shoulder (Conn, Annest, & Gilchrist, 2003; Hawkins & Fuller, 1999; Powel & Barber-Foss, 1999; Schneider, Seither,Tönges, & Schmitt, 2006) injuries. Since a lower level of balance is associated with injuries such as strains and sprains (McGuine, Greene, Best, & Leverson, 2000; Emery & Meeuwisse, 2010; Eils, Schröter R, Schröter M, Gerss, & Rosenbaum, 2010), an incorporation of static and dynamic balance exercises can help reduce the incidence of sports-related injuries among athletes (Brachman et al., 2017).

2.4. Center of Pressure

Different quantitative and qualitative clinical measurements exist to assess postural control. Some of the simplest and most accessible instruments available for quantifying postural control include tape measures, goniometers, and the BESS (Talarico et al., 2017). More complex and expensive instrumentation, such as force plates, can be used to measure the ground reaction force and moments, which can be used to calculate center of pressure (CoP).

Ground reaction force is an external force acting on the body and is largely controlled by coordinated muscle actions (Luhtanen & Komi, 1978). When muscles push against the ground, there is an equal and opposite reaction force from the ground as supported by Newton's Third Law of Motion. Center of pressure is calculated from the ground reaction force and is the point where the ground reaction force vector lies and references the point at which the pressure of the body over the soles of the feet would be if concentrated at a single spot (Ruhe, Fejer, & Walker, 2011). When movement occurs, there are alterations in CoP position, which can be used to postulate how the central nervous system controls the center of mass because CoP controls the movements within a static base of support (Adkin, Frank, & Jog, 2003). The CoP movement characteristics have been used to infer the neurologic and biomechanical mechanisms of postural control (Corriveau, Hébert, Prince, & Raiche, 2000). Various parameters, including sway velocity, sway area, and root-mean-square (RMS), are derived from CoP data in order to quantify alterations in balance (Palmieri et al., 2002).

2.4.1. Speed

Postural sway speed refers to the deviations in the location of the CoP over a given time (Ruhe & Fejer, & Walker, 2010; Ishizaki, Pyykkö, Aalto, & Starck, 1991; Yamamoto et al., 2015; Kouzaki & Shinohara, 2010). Sway speed is attributed to many factors such as inherent noise within the human neuromotor system that is reflected in an anticipatory response or as an output of a controlled process to maintain postural control (Gatev, Thomas, Kepple, & Hallett, 1999; della Volpe et al., 2006; Baratto, Morasso, Re, & Spada, 2002). This speed is often segregated into the medio-lateral or the antero-posterior direction. Previous studies have indicated that an increase in CoP speed is a demonstration of a decrease in postural control (Le Clair & Riach, 1996; Felix, Black, Rodrigues, & Silva, 2017; Baloh, Jacobson, Beykirch, & Honrubia, 1998). In a study concerning static and dynamic posturography in patients with vestibular and cerebellar lesions, Baloh et al. (1998) concluded that as sway speed increases, postural control decreases when patients with bilateral vision loss and cerebellar atrophy perform a static balance test. Sway speed has been shown to indicate the severity of instability and has been used as measure of postural control recovery following an ankle injury in athletes (Hale, Herel, Olmsted-Kramer, 2007). Therefore, clinicians may find using sway speed as a useful measure when quantifying postural control, identifying severity of an injury, and injury management in regaining postural control.

2.4.2. Sway Area

Sway area is defined as the space that contains the entire recorded CoP points (Raymakers, Samson, Verhaar, 2005; Ruhe et al., 2011). Studies examining postural control performance of pathological populations report an increase in sway area and therefore greater postural instability than healthy populations (Adkin et al., 2003; Kent et al., 2012; Ruhe et al., 2011). This parameter is important in yielding information about direction and can be applied to predicting the direction of fall in the elderly population or another population with postural control instability (Baloh, Jacobson, Enrietto, Corona, & Honrubia, 1998). A benefit of using sway area to quantify postural control is that the sensitivity of capturing the CoP deviation corresponds to stability or instability (Kent et al., 2012). Another benefit to using sway area is that this varies greatly between healthy and pathological populations (Harringe, Halvorsen, Renström, & Werner, 2008; Lafond et al., 2009). Lafond et al (2009) found that in a population with non-specific lower back pain exhibited larger sway area compared to a healthy population.

2.4.3. Root-Mean-Square

Center of pressure RMS in general is defined as the square root of the mean squares, or the mean of the squares of a set of numbers (Palmieri et al., 2002). An application of the RMS would be to see an increase in anterior/posterior sway in pain sufferers compared to a healthy population (Brumagne, Janssens, Knapen, Claeys, & Suuden-Johanson, 2008; Brumagne, Janssens L, Janssens E, & Goddyn, 2008). Root-mean-square speed is the distribution of CoP displacements over time (Niam, Cheung, Sullivan, Kent, & Gu, 1999; Baloh, Jacobson, Enrietto, Corona, & Honrubia, 1998; Geurts, Nienhuis, & Mulder, 1993; Geurts, Ribbers, Knoop, & Van Limbeck,1996; Knapp, Frantal, Cibena, Schreiner, & Bauer, 2011; Ledin & Odkvist, 1993). A decreased RMS speed and amplitude is correlated with an increased ability to maintain postural control (Geurts et al., 1993; Amiridis, Hatzitaki, & Arabatzi, 2003; Mancini et al., 2012; Brumagne, Janssens, Knapen, Claeys, & Suuden-Johanson, 2008; Brumagne, Janssens L, Janssens E, & Goddyn, 2008). Geurts et al (1993) reported that RMS amplitude and velocity show sufficient intra-subject consistency over the course of five weeks. Intersession reliability was high for RMS in the antero-posterior ($R = 0.86$) and medio-lateral ($R=0.81$) directions during a double-legged stance (Le Clair & Riach, 1996). Therefore, an increase in either RMS amplitude or velocity suggests a decrease in ability to maintain postural control (Geurts et al., 1993).

2.4.4. Force Plates

A force plate is a clinical instrument used to measure not only ground reaction force, but CoP position and moments. A significant benefit for implementing a portable force plate into testing is that it can be used on the sideline or field and in clinical settings. However, a major limitation to using this higher-level technology is that the equipment is expensive and can be cumbersome to move.

2.5. Single-Leg Postural Control

2.5.1. Assessment

Clinicians have incorporated single-leg balance into lower extremity injury assessments and rehabilitation programs. Single-leg balance stance assesses balance under conditions that introduce additional challenges to the postural control system by simultaneously reducing the base of support (Palmieri et al., 2002). This requires the postural control system to make more adjustments quickly in order to prevent a fall (Palmieri et al., 2002).

2.5.2. Clinical Applications

Though initially thought that single-leg balance depends on leg dominance, several studies have shown that CoP does not differ between dominant and nondominant limbs in a healthy population (Stribley, Albers, Toutellotte, & Cockrell, 1974; Murray, Seireg, & Sepic, 1975; Goldie et al., 1989; Hoffman, Schrader, Applegate, & Koceia, 1998; Chew-Bullock et al., 2012; Kiyota & Fujiwara, 2014); hence single-leg balance assessments are easily applicable for testing postural control of athletes following lower leg injury to compare involved and uninvolved limbs. Clinicians should caution though when comparing performance on an involved limb to an uninvolved limb because bilateral change might occur with injury, making the limb comparison invalid or less reliable (Palmieri et al., 2002). The number of touchdowns, or when the elevated foot touches any part of the ground, that occurs during a trial period demonstrates postural instability of an individual (Palmieri et al., 2002). An inverse relationship between touchdowns and postural control has been investigated by numerous researchers especially those concerned with ankle stability (Pinstaar, Brynhildsen, & Tropp, 1996; Ringhof, Stein, Hellmann, Schindler, & Potthast, 2016).

2.6. Single Task Paradigm

2.6.1. Definition

A single-task (ST) paradigm is the performance of one task or assessment independently of others where the participant only focuses their attention on that task at hand (Teel et al., 2013; Ingriselli et al., 2014; Bugg, et al., 2008). Tasks completed under a ST paradigm may include anything from clicking a mouse each time a color changes (Park, Salsbury, Corbett, & Aiello, 2013) to gait (Bohannon, 1997) to Stroop color-word association (Pilli et al., 2013; Bayard et al., 2011; Djamshidian et al, 2010; Bugg et al., 2008).

2.6.3. Clinical Applications

Being able to focus on one specific task at a time has the added advantage of dedicating nearly all of one's attention to completing that task (Ingriselli et al., 2014; Park et al., 2013). Single-task assessments measure the ability to track and respond to information over extended periods of time and perform these tasks as quickly and accurately as possible in healthy (Ingriselli et al., 2014; Tsang et al., 2016) and pathological (King & Hux, 1996; LaPointe & Erickson, 1991; Murray, Holland, & Beeson, 1997; Murray, Holland, & Beeson, 1998; Murray, 2000; Tseng, McNeil, & Milenkovic, 1993) populations.

When suspecting injury, motor or cognitive ST assessments are efficient and simple. As a popular cognitive task, the Stroop test measures the number of correct responses and response times for each participant to quantify performance (Bugg et al., 2008; Ingriselli et al., 2014; Park et al., 2013; Chen, Lu, & Chou, 2015; Pilli et al., 2013; Djamshidian et al., 2011; Cempaka, ArRochmah, & Nurputra, 2015). By comparing values between healthy and injured athletes, clinicians may be able to distinguish cognitive deficits to guide rehabilitation and injury management. For motor STs, CoP position, CoP velocity, and displacement coordinates of postural sway are just a few of the variables that can be measured (Janusz et al., 2016). By isolating either motor or cognitive components, clinicians are able to specifically test the athlete for injury by limiting confounding variables.

2.7. Dual-Task Paradigm

2.7.1. Definition

Because there is a limited capacity for memory, dual-task (DT) paradigms divide attention between two or more tasks concurrently which can result in decrements in performance in one or both of the tasks relative to when they are performed under ST (Plummer & Eskes, 2015; Abernethy, 1988; Tsang et al., 2016; Ingriselli et al., 2014; Kerr, Condon, & McDonald, 1985; Dault, Geurts, Mulder, & Duysens, 2001). The relative change in performance associated with DT is referred to the dual-task interference or the dual-task effect (DTE) (Plummer & Eskes, 2015). A benefit for employing this paradigm is that simultaneously measuring motor and cognitive performance provides additional information regarding the two domains that are affected by concussion (Broglio & Puetz, 2008; Catena et al., 2009; Moser et al., 2007). A cognitive test, like Stroop, that is performed while walking provides information about conflict resolution by eliciting responses in a congruent or incongruent manner to probe executive function (Howell et al., 2013). Executive function is shown to be significantly affected by sports-related injuries (Catena, van Donkelaar, & Chou, 2011; Halterman et al., 2006). Consequently, DT paradigms using the Stroop test prove beneficial in probing how an individual will perform when engaging in the regular activities of daily living during recovery (Howell et al., 2013). Although DT provides a plethora of information, two limitations to this paradigm are not being able to determine concussion severity (Barr, Prichep, Chabot, Powell, & McCrea, 2012) or the variability in results between different injuries (Howell et al., 2013).

2.7.2. Clinical Applications

Dual-task paradigms are most commonly associated with a cognitive task and a motor task. It is proposed that DT paradigms more closely reflect an individual's performance than ST paradigms because of the dynamics and multi-faceted nature of daily activities (Plummer & Eskes, 2015; Park et al., 2013; Ingriselli et al., 2014). An example of a DT paradigm would be walking (motor) and talking on the phone (cognitive). Dual-task paradigms involving ambulation have become components of motor performance rehabilitation for individuals with neurological disorders (Brauer et al., 2011; Kelly, Eusterbrock, & Shumway-Cook, 2012; Plummer-D'Amato et al., 2012) because walking is associated with quality of life (Astrom, Adolfsson, & Asplund, 1993; Bond, Clark, Smith, & Harris, 1995; Roos, Rudolph, & Reisman, 2012). Considering athletics, DT paradigms are thought to better represent performance because of the simultaneous processing of information between motor and cognitive processes required in sports (Broglio et al., 2005; Parker et al., 2008; Ingriselli et al., 2014). Sports-related head injuries have been found to decrease attention resources which influences cognitive processing and increases motor reaction time with various tasks (Sosnoff et al., 2008; Collins et al., 2003; Erlanger et al., 2003; Sosnoff, Broglio, Hillman, & Ferrara, 2007). Similarly, clinicians are able to monitor progress or guide decisions for return-to-play by using DT paradigms compared to traditional ST paradigms (Catena et al., 2007a; Catena et al., 2007b; Catena et al., 2009). Implementing DT paradigms can also yield information about task prioritization, or whether a population tends to prioritize the motor or cognitive task (Tsnag et al., 2016). For instance, Tsang et al. (2016) observed longer reaction times and more errors of an elderly population under DT compared to ST. Since postural control was prioritized over cognition, the study was able to conclude that the fear of falling or loosing balance prompted the prioritization (Tsang et al., 2016).

Chapter 3: Methodology

3.1. Participants

This study included 18 physically active, healthy college students (four males, 20.78±1.06 yrs., 168.49±9.10 cm, 63.88±7.90 kg) who volunteered to participate. No participants reported neurological, vestibular, auditory or visual conditions or deficits. Participants self-reported no injuries to the lower extremity or a medically-diagnosed concussion within six months before the start of data collection. Prior to testing, participants signed an institutional review board approved informed consent form. The Ohio State University's Institutional Review Board approved the experimental protocol.

3.2. Instrumentation

Stroop tests were performed on a computer positioned at eye level to the participant. Participants stood on a tri-axial force plate (Bertec Corporation, Columbus, Ohio) during all assessments. Bertec Digital Acquire™ software collected CoP position data from the force plate throughout each trial.

3.3. Procedure

Participants performed a single-leg balance test and two variations of the Stroop test under ST (Figure 1) prior to DT (Figure 2). Participants performed the single-leg balance assessment to evaluate postural control. Participants were instructed to place hands on hips, maintain forward gaze towards the computer, and flex the non-stance knee and hip at approximately 45° with the stance foot remaining in contact with the ground throughout the entire test. The examiner recorded errors during the single-leg balance assessment which included: 1) hands lifted off iliac crest, 2) non-stance foot touched the ground, 3) hip abduction more than 30°, and 4) lifted the stance forefoot or heel off of the ground. Participants were asked to stand on their dominant leg (i.e. the leg with which they would kick a soccer ball furthest) during the single-leg balance test for 20 seconds. Any deviation from these instructions was counted as a balance error.

The two Stroop tests implemented were the $Stroop_{single}$ (Figure 3) and $Stroop_{multiple.}$ (Figure 4). A presentation of a color-word was referred to as a "stimulus" during testing. Congruent and incongruent stimuli were randomly presented. Congruent stimuli were identified as a color-word in which the color name (red, blue, yellow, green) and color font (red, blue, yellow, green) matched (e.g. the word 'red' was in font color red). Incongruent stimuli were identified as a color-word in which the color name and color font did not match (e.g. the word 'red' was in font color green). The order of congruent and incongruent stimuli was randomly presented. The $Stroop_{single}$ test consisted of 24 stimuli each presented on a black background in Times New Roman font size 40. Each stimulus appeared for two seconds upon which the participant was instructed to recite the color of the word as quickly and as accurately as possible. Total time for a single trial of $Stroop_{single}$ lasted 48 seconds. $Stroop_{multiple}$ was conducted in a similar method to $Stroop_{single}$; however, during $Stroop_{multiple}$ 24 stimuli were presented on a single slide, organized in a six-by-four grid. Participants were instructed to recite the color of the words as quickly and accurately as possible. Instructions were given to start with the top left stimulus, continue down the column, then move to the first stimulus in the second column and continue this pattern. If participants completed $Stroop_{multiple}$ in less than the maximum allotted 48 seconds, the completion time was recorded.

Table 1 provides further description of the ST and DT testing paradigms. The order in which participants performed $Stroop_{multiple}$ and $Stroop_{single}$ was randomized. Under DT paradigms, participants were instructed to recite the font color of the color-word as quickly and as accurately as possible while maintaining postural control to the best of their ability. No instructions were provided for participants to prioritize one task over the other. Three trials for ST and DT conditions were completed for all tasks. Participants were provided with a 1-minute rest before the next trial to prevent fatigue. The Stroop tests completed under ST were different than those completed under DT for each participant. The order in which each Stroop test was presented for ST and DT paradigms was randomized.

3.4. Data Reduction

Total number of responses attempted by each participant were recorded for all trials. Correct congruent and incongruent responses were recorded separately and divided by total number of responses attempted to calculate response accuracy. The number of correct congruent responses was defined as ResponsesC and was presented as a percent; likewise, the number of correct incongruent responses was defined as ResponseI and was presented as a percent.

The CoP outcome variables calculated to quantify postural control were total, medio-lateral (ML), and antero-posterior (AP) sway speed (cm/s), and 95% elliptical sway area (cm^2/s) (Table 2). Center of pressure data were collected at 1000 Hz with a fourth-order zero lag Butterworth filter with lowpass filter at 20 Hz. The first and last five seconds of each single-leg balance trial under ST were excluded from analysis in order to account for initially raising the leg and the anticipating the end of the test. Balance error scores were also recorded.

Due to end of trial anticipation and human error with manual timing, the end of some trials during DT $Stroop_{single}$ and DT $Stroop_{multiple}$ had unreliable vertical ground reaction force (vGRF) patterns. For example, there were some instances were vGRF decreased to zero at the end of the trial, indicating that the participant stepped off the force plate prematurely in anticipation to the trial's conclusion. Including these data in the analyses would inappropriately characterize postural control performance during the task or assessment. Therefore, we applied a data trimming method to remove such data from analysis. Average vGRF was calculated during the three single-leg stance trials completed under ST. The average of these three trials was used as the baseline vGRF for the data trimming method. This method is presented in Figure 5. vGRF data points were identified if they were above or below 5% of the average vGRF. The data was compared to the BESS errors recorded to ensure that there were no errors present at that time that could have caused the force to be above or below 5% of average vGRF. The last 10%, 15% and 20% of a trial was identified as well (e.g. the last 10% of a 25 second trial was 22.5 to 25 seconds). If a data point was above or below the 5% average vGRF threshold, was not due to a BESS error, and fell within 10% of the end of the trial, that data point and all data points following until the end of the trial were excluded from analyses. This method was also applied to the last 15% and 20% of a trial. Outcome variable means were averaged across the three trials for each condition. The overall condition mean was used for analyses.

3.5. Statistical Analysis

Repeated measures one-way ANOVAs were performed to determine if performance difference existed between testing paradigms (ST and DT) for each outcome variable. Alpha level was set *a priori* at 0.05. All analyses were performed using Statistical Package for the Social Sciences (SPSS) version 24 (SPSS, Inc., Chicago, IL).

Chapter 4: Results

Overall, there were no differences in trial times between the original time, following data trimmed within the last 10%, 15%, and the 20% of trials ($p>0.05$) under DT with $\text{Stroop}_{\text{single}}$ (Table 3) and under DT with $\text{Stroop}_{\text{multiple}}$ (Table 4). There were also no differences in outcome variable means between the data trimming methods ($p>0.05$). All means and results presented in this paper will be from the 10% trimming method. Tables 5 and 6 present the cognitive and postural control results for each condition respectively.

4.1. Correct Congruent Response

ResponseC was not different between ST (99.49±1.77 %) and DT with $\text{Stroop}_{\text{single}}$ (100.00 ±0.00 %) ($F_{1,17}$, $p=0.24$). ResponseC was not different between ST (98.89±3.23%) and DT with $\text{Stroop}_{\text{multiple}}$ (99.81±0.79%) ($F_{1,17}=2.46$, $p=0.14$).

4.2. Correct Incongruent Response

No differences were observed for ResponseI between ST (98.66 ±1.53 %) and DT with $\text{Stroop}_{\text{single}}$ (98.56±1.86 %) ($F_{1,17}=0.07$, $p=0.79$). Additionally, no differences were observed for ResponseI between ST (98.81±1.68 %) and DT with $\text{Stroop}_{\text{multiple}}$ (98.68±2.48 %) ($F_{1,17}=0.03$, $p=0.86$).

4.3. Sway Speed

Overall, total sway speed was influenced by the test condition ($F_{2,34}=9.88$, $p<0.01$). Post-hoc pairwise comparisons revealed that total sway speed was slower under DT with $\text{Stroop}_{\text{single}}$ (2.86±0.71 cm/s) and DT with $\text{Stroop}_{\text{multiple}}$ (3.72±1.85 cm/s) than under ST (4.24±1.89 cm/s) ($\text{Stroop}_{\text{single}}$: $p<0.01$; $\text{Stroop}_{\text{multiple}}$: $p=0.04$). Total sway speed under DT with $\text{Stroop}_{\text{multiple}}$ was slower than that under DT with $\text{Stroop}_{\text{single}}$ ($p=0.02$). A test condition main effect was also observed for ML sway speed ($F_{2,34}=8.57$, $p<0.01$). ML sway speed was slower under DT with

$Stroop_{single}$ (1.70±0.31 cm/s) compared to DT with $Stroop_{multiple}$ (2.33±1.19 cm/s) ($p=0.02$) and under ST (2.50±0.94 cm/s) ($p<0.01$). There was no difference in ML sway speed between DT with $Stroop_{multiple}$ and ST ($p=0.34$). Similarly, AP sway speed was influenced by test condition ($F_{2,34}=8.57$, $p<0.01$). Post-hoc pairwise comparisons revealed that AP sway was slower under DT with $Stroop_{single}$ (1.94±0.61 cm/s) and under DT with $Stroop_{multiple}$ (2.44±1.35 cm/s) than under ST (2.89±1.47 cm/s) ($Stroop_{single}$: $p<0.01$; $Stroop_{multiple}$: $p=0.03$). AP sway speed under DT with $Stroop_{multiple}$ was faster than that under DT with $Stroop_{single}$ ($p=0.05$).

4.4. Sway Area

There was a test condition main effect on sway area ($F_{2,34}=10.44$, $p<0.01$). No differences in sway area were observed between DT with $Stroop_{multiple}$ (0.69±0.64 cm^2/s) and ST (0.91±0.78 cm^2/s) ($p=0.29$). Sway area was smaller under DT with $Stroop_{single}$ (0.14±0.07cm^2/s) compared to that under ST ($p<0.01$). Sway area was smaller under DT with $Stroop_{single}$ than under DT with $Stroop_{multiple}$ ($p<0.01$).

Chapter 5: Discussion

Dual-task paradigm influenced single-leg postural control performance but did not influence Stroop performance. These findings suggest that the cognitive task was demanding enough to influence the motor component. Innately, balance requires less attentional resources to complete because of its incorporation into everyday life (Tsang et al., 2016; Ingriselli et al., 2014; Talarico et al., 2017). Because attention is limited, a more demanding task could require more attentional resources to complete. This in turn decreases the attention devoted to another task in the DT paradigm, in this study the motor task. When less attention resources are supplied, one's performance of the task is influenced. In this study, cognitive performance did not differ between ST and DT for both variations of the Stroop test. However, compared to ST, total sway speed decreased under both DT with $\text{Stroop}_{\text{single}}$ and $\text{Stroop}_{\text{multiple}}$, ML sway speed decreased under DT $\text{Stroop}_{\text{single}}$, AP sway speed was slower under DT with $\text{Stroop}_{\text{single}}$ and $\text{Stroop}_{\text{multiple}}$, and sway area was smaller under DT with $\text{Stroop}_{\text{single}}$. Participants seemed to prioritize the Stroop assessments ahead of the single-leg balance, possibly due to the unfamiliarity of the cognitive task in comparison to the motor task. These findings suggest that the task difficulty and task familiarity to the participant should be considered when interpreting differences in performance between ST and DT paradigms.

If allocating undivided attention to a task, execution of the task will likely be more successful compared to instances when attention is distracted by simultaneous tasks (Künstler et al., 2017). These findings highlight the importance of evaluating an individual's performance under both ST and DT paradigms because they may not be alike. Considering rehabilitation, the incorporation of the DT paradigm into a clinical setting can allow clinicians to set goals for their patients (i.e. improve their balance under a DT paradigm). By training a patient in a specific DT paradigm, clinicians are able to see if improvements in a task are being made without undermining the other task. The DT paradigm may also be utilized to see what task the patient is prioritizing; this then lends the question as to why is that patient prioritizing that specific task. When thinking of an elderly patient, the prioritization of the motor task compared to the cognitive task may reflect their fear of falling. The clinician can then use prioritization to train and improve the patient's balance. Additionally, DT paradigms allow clinicians to evaluate an athlete's performance comprehensively or how they would function in their everyday life. On the field, quick decision-making is crucial for the success of an athlete. Therefore, the utilization of a DT paradigm is critical to ensuring that an athlete is making good decisions on and off the field to ensure their safety.

5.1. Cognitive Assessment Differences

There were no significant differences between cognitive performances when performing Stroop under single-task and when performing concurrently with single-leg balance. This observation refutes our hypothesis that cognitive performance would decrease when Stroop is performed with single-leg balance. The balance task may not be challenging enough to influence changes in cognitive performance as balance may require less attentional resources, which can lend more resources to completing the cognitive component. Previous studies have also found that cognition remained unaffected between ST and DT performance (Tsang et al., 2016, Remaud et al., 2013; Ingriselli et al., 2014; Talarico et al., 2017). Other studies have reported cognitive DT deficits following concussion (Broglio & Puetz, 2008; Catena et al., 2009; Moser et al., 2007; Azouvi et al., 2004; Teel et al., 2013; Sosnoff et al., 2008; Collins et al., 2003; Erlanger et al., 2003; Sosnoff et al., 2007); therefore, not all Stroop assessments or populations tested will yield the same results. It is important for clinicians to consider a patient's prior exposure to cognitive tasks as well as using the same cognitive protocol from a patient's initial assessment all the way through their rehabilitation to minimize confounding variables.

Within this study, the cognitive task required more attention than the motor task because of its difficulty relative to the single-leg balance. Because balance is a part of our everyday life, our population voluntarily or involuntarily prioritized completing the unfamiliar Stroop tests accurately ahead of balance. It is possible that both the cognitive and the motor tasks selected for this study were not challenging enough to provoke obvious performance changes. However, the lack of cognitive variability between ST and DT suggests that in order to maintain accuracy, participants had to prioritize the Stroop task ahead of the balance task.

5.2. Static Postural Control Differences

Previous studies have reported a decrease in postural control under DT paradigms compared to ST (Ingriselli et al., 2014; Hall, Echt, Wolf, & Rogers, 2011; Brauer, Broome, Stone, Clewett, & Herzig, 2004; Swan, Otani, & Loubert, 2007). Brauer et al. (2004) found that static postural control of brain-injured patients under a DT paradigm resulted in increased CoP excursions and velocity when compared to ST. When comparing Brauer et al.'s results to the findings from this study, the addition of the cognitive task to create the DT paradigm is likely the contributing factor to the differences in CoP measures when compared to ST. Similarly, Hall et al. (2011) reported a decrease in gait speed and dynamic postural control due to the impact of adding a difficult cognitive component. Because ST does not require attention to be divided, postural control performance under this paradigm is expected to be more stable than DT. However, this is not what the results suggest in this study. Instead, the decreased sway speeds and smaller sway area in this study suggest postural stability under DT when compared to ST. Yet, the change in CoP parameters between ST and DT illustrates a significant change in stability among individuals. These changes in stability when operating under different paradigms helps clinicians understand how our stability is adjusted so clinicians can identify potential injury risks. Similar to this study, other studies declare that there is change in stability other than a decreased postural control under DT.

Studies have also reported improvements or no changes in motor performance between ST and DT. Two significant studies both conducted by Silsupado et al. (2006 & 2009) found that in older populations, training under a DT paradigm improved their gait performance compared to ST. When implementing a DT paradigm comprised of visual and auditory conditions, Picou & Ricketts (2014) reported neither visual nor auditory performance changed between ST and DT. One explanation to these findings is that some of the auditory and visual tasks utilized were not sensitive enough to detect changes. Both the Silsupado et al. (2006 & 2009) studies and the Picou & Ricketts (2014) study incorporated DT; however, both studies had entirely different motor outcomes and populations. Therefore, DT paradigms will behave differently depending not only on the tasks presented but the population being tested.

Because CoP differed under the DT paradigm compared to ST, this study suggests that there were fewer attentional resources allocated towards completion of the single-leg balance test due to the increased resources needed to complete the cognitive task. Since attentional resources are limited and need to be shared between two tasks performed concurrently (Künstler et al., 2017), Stroop might have required a greater attentional demand to complete the task compared to the relatively simple single-leg balance task. In reference to balance changes, when greater attentional resources are devoted to Stroop under DT, fewer resources are left for balance. If a perturbation to the system occurs, the participant may not have enough resources available to make quick adjustments needed to maintain stability. There were only four balance errors recorded in this study which all occurred under DT. Although participants may have exhibited postural stability indicated by the BESS, it is as equally important to consider the more subtle CoP changes in order to comment upon a participant's stability.

The CoP movement characteristics have been utilized by clinicians to determine if any neurological or biomechanical abnormalities are present. However, caution should be taken when using changes in CoP measures as a proxy for postural stability for healthy individuals. There are many components besides CoP parameters that contribute to stability such as vision, injury, or recent surgery (Chang, Lim, Lee, & Moon, 2014). With this in mind, it may not be appropriate to comment upon this population's stability but more so that there was a change in motor performance between ST and DT paradigms. Therefore, a major objective of this study was to focus on quantifying postural control performance via laboratory measures rather than clinical measures. But clinical measures, such as the BESS, have an invaluable importance as well. When applying the trimming method to this study, it was necessary to refer to the BESS errors recorded in order to ensure that the data points above or below the 5% average vGRF threshold were due to participant or experimenter error and not a participant's loss of balance. Without the BESS, the incorporation of the trimming method would be inappropriate because it would have altered the results of the study without having a clinical tool to justify the exclusion of data that might be considered a postural control error.

Since individuals often perform multiple tasks concurrently, DT assessments are crucial for providing comprehensive information concerning an individual's postural control performance under paradigms that better reflect everyday activities. Compared to the cognitive task, the single-leg balance assessment may not have required as many attentional resources. In this study, perhaps the Stroop cognitive task occupied a larger portion of attentional resources, unintentionally leaving the single-leg balance with fewer resources and the body's need to make adjustments. This would explain why postural control differed under DT compared to ST.

5.3 Comparison of ST to DT

Overall, individuals displayed slower total, ML, and AP sway speeds and a smaller sway area under DT when compared to ST. These observations refute our hypotheses that participants will display a faster total, ML and AP sway speed and larger sway area under DT when compared to ST. Nevertheless, the differences present in this study's findings suggest that performing two tasks simultaneously has an impact on performance. Due to the possible increase in attentional recourses required to perform the additional task under DT, changes in the motor task were expected to occur. Alterations in head movement (Johansson & Magusson, 1991; Dietz, 1992, Johansson, 1993; Magnus, 1924), hip movement (Nashner & McCllum, 1985), and ankle movement (Docherty et al., 2006; Freeman, 1965; Hertel & Olmstead-Kramer, 2007; Konradsen & Rayn, 1991; Troop 1986, Troop et al., 1985) are implemented in order to position the body upright and stable. When muscles are not adjusting fast enough, an increased risk of falling could occur because humans cannot maintain stability through unchanging muscular activity (Loram, Maganaris, & Lakie, 2005). Though balance does not require conscious thought, without some attentional resources devoted to postural control, the body would not be able to take proactive measures to combat outside interference or instability (Lakie, Caplan, & Loram, 2003). Therefore, the difference between ST and DT paradigms shown in this study could be due to the body shifting resources away from the innate single-leg balance in order to compete with increasing demands of the cognitive task. Considering a pathological population, it would be valuable for a clinician to incorporate a DT paradigm so one could assess if the patient is capable of adapting to increasing demands or is capable of prioritizing one task over another to promote safety. Due to the dynamic nature of life, it is crucial to assess patients using a DT paradigm to ensure their safe and healthy recovery.

In this study, the commitment of balance errors made under DT may not be a direct indication of postural instability. Many factors contribute towards stability, such as vision, injury, or surgery history (Chang et al., 2014). These results simply suggest that when two variations of Stroop are performed in conjunction with a single-leg balance, there is a significant difference between a participant's ST and DT performance. These four total balance errors committed under DT do suggest postural instability, but they are relatively inconsequential compared to the potential balance errors that could have been committed when 18 participants each performing six DT trails. Considering CoP measures, a change in parameters between ST and DT suggests instability (Plummer & Eskes, 2015; Abernethy, 1988; Tsang et al., 2016; Ingriselli et al., 2014; Kerr, Condon, & McDonald, 1985; Dault, Geurts, Mulder, & Duysens, 2001), but the few BESS errors that were recorded suggests stability. Therefore, clinicians should practice caution when solely relying on BESS to determine stability. Instead, using CoP measures to help understand how stability is adjusted under different paradigms to maintain is a more sensitive and accurate way of monitoring stability.

5.4. Comparison between Stroop variations under DT

Many different variations of the Stroop test have been implemented into practice. The two variations in this study were modeled after a more traditional model which this study referenced as $\text{Stroop}_{\text{single}}$ (Djamshidian et al., 2011; Pilli et al., 2013), and a more modern model which this study referenced as $\text{Stroop}_{\text{multiple}}$ (Bayard et al., 2011). The main difference between the two variations is the presentation of the stimuli on either one slide at a time or all on the same slide. Because of the inherent demands of the task, participants incorporated a visuomotor component while completing the Stroop$_{multiple}$ to trace stimuli as opposed to the Stroop$_{single}$ assessment where fixed center gaze was sufficient enough to perform the task. When incorporating peripheral vision or a full field of vision into a study, participants display a smaller postural sway than the central vision field when focusing on a computer display with varied fields of vision (Berensci, Ishihara, & Imanaka, 2005). The difference in stimulus presentation coincides with the study's slowing of total, ML, and AP sway speed and the smaller sway area under DT with Stroop$_{single}$ and under DT with Stroop$_{multiple}$.

Based off of the findings from this study, it is important for clinicians to consider not only the type of assessment but also how that assessment is being incorporated into practice. For instance, this study implemented two common Stroop assessments. One of the key differences in these assessments was their visuomotor component, which perhaps is a more clinically relevant assessment. Because tasks such as driving, running a forward pass, or reading a book all require a dynamic field of vision, administering a test such as Stroop$_{single}$ may not be the most accurate representation of an individual's proactive capabilities. In addition to the Stroop test, other cognitive assessments such as a Serial Seven's test or reciting the alphabet backwards may require the participant to practice a skill needed to correctly complete the test. Because these cognitive tests are not naturally incorporated into daily routine, clinicians should be aware that a participant's initial performance on a cognitive task might inaccurately reflect their cognitive capacity.

5.5. Limitations

This study was not without its limitations. The height of the laptop was consistent between participants, although the tilt of the laptop was adjusted. This is a limitation because a taller participant has to focus his or her gaze downward more so than someone of a smaller stature. To mitigate this issue, having an adjustable laptop stand, similar to mobile physician desks, would be ideal. Considering the environment of the study, noise and visual distractions were not controlled. Because of the proximity to the physical therapy clinic, the dropping of weights or talking among patients could have been distracting to the participant. Finally, only one experimenter conducted this study. Considering DT, one experimenter was responsible for starting and stopping the force plate, grading the Stroop test, and inspecting for BESS errors. It is possible that BESS errors were overlooked or Stroop responses were graded incorrectly because only one experimenter was conducting the study.

5.6. Future Research

Clinicians should consider incorporating DT into evaluations with appropriate motor and cognitive tasks to comprehensively assess functional and cognitive performances (Plummer & Eskes, 2015; Park et al., 2013; Ingriselli et al., 2014). Performing two tasks concurrently may better reflect how athletes or other populations handle day-to-day activities. Future researchers should consider assessing a larger population of healthy and pathological participants to determine normalized DT performance as a baseline measure to compare to following an injury. Formatting a Stroop assessment to the individual being evaluated should be considered. For example, a Stroop assessment that incorporates a visuomotor component to trace color-word stimuli may too taxing on the system for acute testing following a concussion.

Since this study only focused on one motor component and one cognitive component, future research would benefit from experimenting with different motor and cognitive tasks. Instead of focusing on static balance tests, incorporating a dynamic task such as walking on a balance beam in conjunction with a cognitive task might influence cognition more than the single-leg balance task. In addition to divided attention tasks like Stroop, future research could focus on reaction time tests, attention span, short- and long-term memory, or judgment.

5.7. Conclusion

Postural control performance, regardless of Stroop version, was different between single-task and dual-task paradigms where no differences were observed with cognitive performance. This might indicate that participants allocated more attentional resources to the cognitive task since it may have been more challenging than the motor task. Designating more attentional resources to the cognitive task may have taken attention away from the single-leg balance task resulting in postural control changes between ST and DT. Clinicians should consider incorporating DT into evaluations with appropriate motor and cognitive tasks to comprehensively assess functional and cognitive performances and to guide return-to-play decisions and injury management. Dual-task evaluations allow clinicians to performance in comprehensive manner to better assess motor and cognitive capabilities. By utilizing the DT paradigm, clinicians mimic an individual's environment to provide the best care and treatment plan possible.

Figure 1: Cognitive assessment performed under single-task paradigm

Figure 2: Cognitive and motor assessments performed under dual-task paradigm

Figure 3: Example of $\text{Stroop}_{\text{single}}$, showing an incongruent stimulus

Figure 4: Example of $\text{Stroop}_{\text{multiple}}$, showing incongruent and congruent stimuli

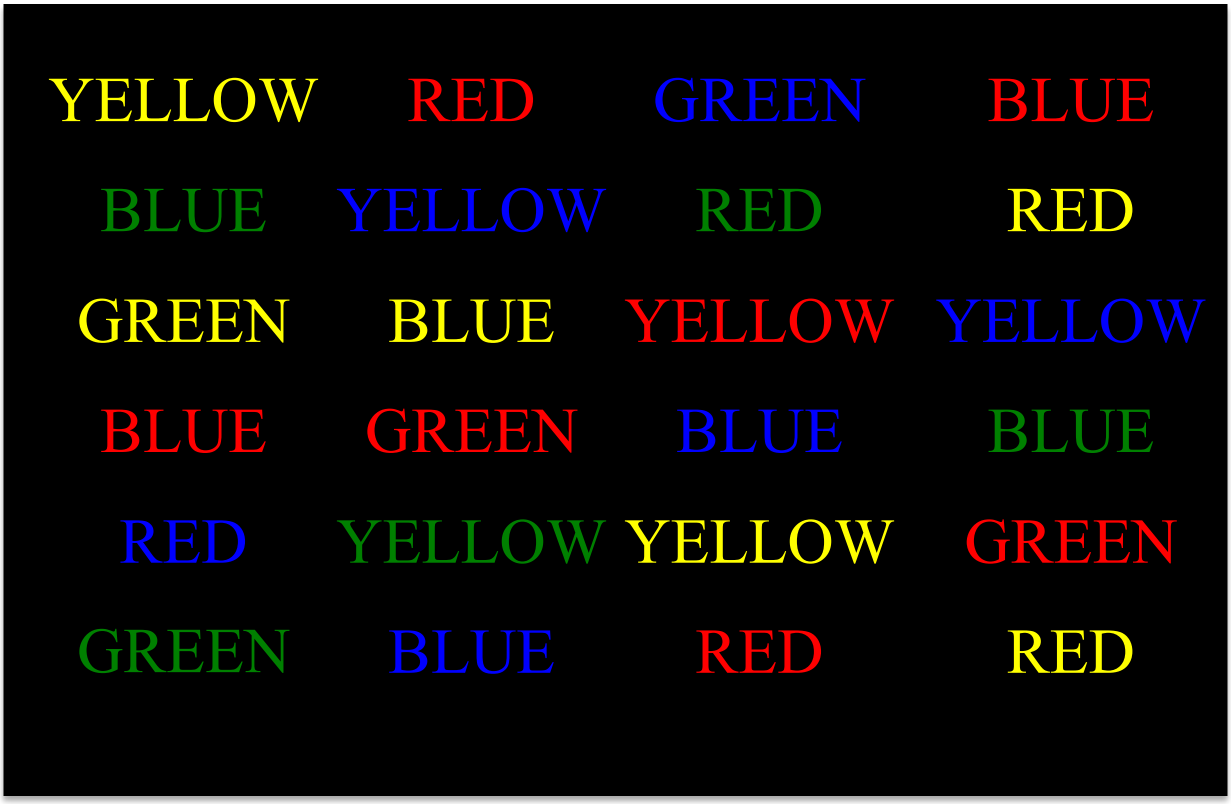

Figure 5: Trimming method decision process.

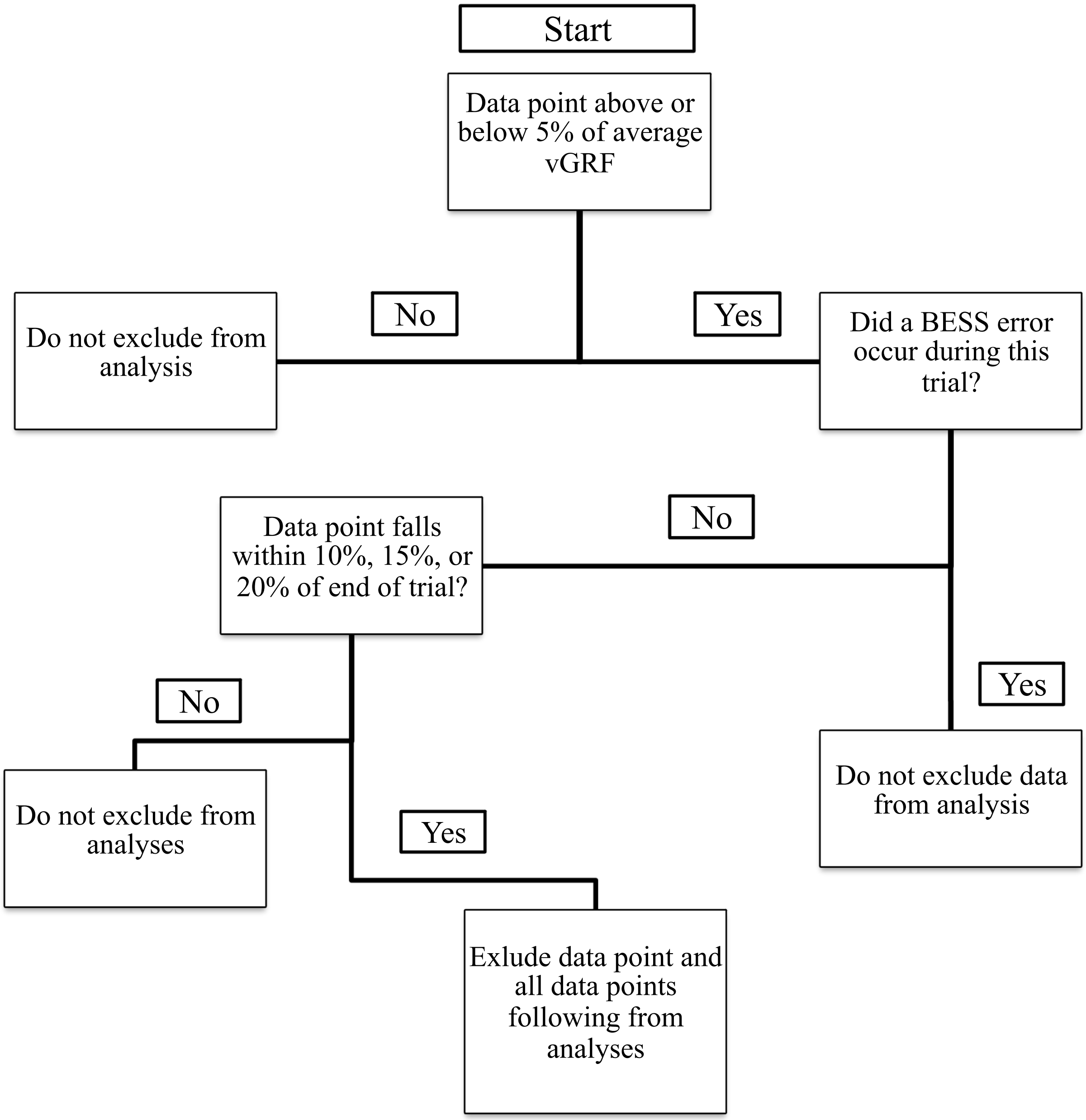

Table 1: Testing conditions completed by all participants to test postural control and cognitive performance.

Condition	Motor Assessment	Cognitive Assessment	Paradigm
1	None	$Stroop_{single}$	ST
2	None	$Stroop_{multiple}$	ST
3	single-leg balance	None	ST
4	single-leg balance	$Stroop_{single}$	DT
5	Single-leg balance	$Stroop_{multiple}$	DT

Abbreviations: ST = single-task; DT = dual-task; $Stroop_{single}$ = single-stimulus Stroop; $Stroop_{multiple}$ = multiple-stimuli Stroop

Table 2: Definitions and formulae of postural control outcome variables

Variable	Unit	Definition	Formula
Total sway speed	cm/s	Trial time normalized center of pressure (CoP) excursion in the combined antero-posterior and medio-lateral directions	$\frac{\sum \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2}}{time}$
Antero-posterior (AP) sway speed	cm/s	Trial time normalized center of pressure excursion in the AP direction	$\frac{\sum \sqrt{(x_{n+1} - x_n)^2}}{time}$
Medio-lateral (ML) sway speed	cm/s	Trial time normalized center of pressure excursion in the ML direction	$\frac{\sum \sqrt{(y_{n+1} - y_n)^2}}{time}$
Sway Area	cm^2/s	Trial time normalized statistically based estimate of a confidence ellipse that encloses approximately 95% of the points of the center of pressure trajectory	$2\pi F_{.05[2,N-2]}\sqrt{S_{AP}^2 S_{ML}^2 - S_{APML}^2}$ S_{AP} and S_{ML} are the standard deviations of the AP and ML times series S_{APML} represents their covariance

Table 3: Mean trial times in seconds between the original time and 10%, 15%, and the 20% trimming methods under DT Stroop$_{single}$.

	DT Stroop$_{single}$ Trial Times			
	Original time Mean ± Stdev	Trimmed 10% Mean ± Stdev	Trimmed 15% Mean ± Stdev	Trimmed 20% Mean ± Stdev
Trial 1 (s)	48.00 ± 0.00	47.99 ± 0.05	47.99 ± 0.05	47.99 ± 0.05
Trial 2 (s)	48.00 ± 0.00	45.33 ± 11.31	45.33 ± 11.31	42.66 ± 15.52
Trial 3 (s)	48.00 ± 0.00	48.00 ± 0.00	47.39 ± 2.60	47.39 ± 2.60
Average (s)	48.00 ± 0.00	47.11 ± 3.79	46.90 ± 3.84	46.01 ± 5.18

Abbreviations: ST = single-task; DT = dual-task; Stroop$_{single}$ = single-stimulus Stroop; Stdev = standard deviation

Table 4: Mean trial times in seconds between the original time and 10%, 15%, and the 20% trimming methods under DT Stroop$_{multiple}$.

	DT Stroop$_{multiple}$ Trial Times			
	Original time Mean ± Stdev	Trimmed 10% Mean ± Stdev	Trimmed 15% Mean ± Stdev	Trimmed 20% Mean ± Stdev
Trial 1 (s)	18.33 ± 5.28	16.85 ± 3.56[a]	16.78 ± 3.49[a]	16.53 ± 3.82[a]
Trial 2 (s)	18.24 ± 4.66	16.78 ± 3.12[a]	16.76 ± 3.11[a]	16.55 ± 3.25[a]
Trial 3 (s)	17.45 ± 4.18	15.88 ± 2.47[a]	15.61 ± 2.35[a]	15.61 ± 2.35[a]
Average (s)	18.00 ± 4.38	16.50 ± 2.79[a]	16.38 ± 2.71[a]	16.23 ± 2.82[a,b]

Abbreviations: ST = single-task; DT = dual-task; Stroop$_{multiple}$ = multiple-stimuli Stroop; Stdev = standard deviation

[a]Significantly different than original time

[b]Significantly different than trimming data within the last 10% of a trial

Table 5: Percent of correct congruent (ResponseC) and incongruent (ResponseI) responses in $Stroop_{single}$ and $Stroop_{multiple}$ for each paradigm.

	$Stroop_{single}$		**$Stroop_{multiple}$**	
	ST Mean ± Stdev	DT Mean ± Stdev	ST Mean ± Stdev	DT Mean ± Stdev
ResponseC (%)	99.49 ± 1.77	100.00 ± 0.00	98.66 ± 1.53	98.56 ± 1.86
ResponseI (%)	98.89 ± 3.23	99.81 ± 0.79	98.81 ± 1.68	98.68 ± 2.48

Abbreviations: $Stroop_{single}$ = single-stimulus Stroop; $Stroop_{multiple}$ = multiple-stimuli Stroop; ST = single-task; DT = dual-task; ResponseC = correct congruent response; ResponseI = correct incongruent response; Stdev = standard deviation

Table 6: Mean values ± standard deviations for postural control variables for all conditions following the last 10% trimming method applied to all DT trials.

	ST Mean ± Stdev	DT with Stroop_{single} Mean ± Stdev	DT with $\text{Stroop}_{multiple}$ Mean ± Stdev
Total Sway Speed (cm/s)	4.24 ± 1.89	2.86 ± 0.71[a]	3.71 ± 1.85[a,b]
ML Sway Speed (cm/s)	2.50 ± 0.94	1.70 ± 0.31[a]	2.33 ± 1.19[b]
AP Sway Speed (cm/s)	2.89 ± 1.47	1.94 ± 0.61[a]	2.45 ± 1.35[a,b]
Sway Area (cm^2/s)	0.91 ± 0.78	0.14 ± 0.07[a]	0.69 ± 0.64[b]

Abbreviations: ST = single-task; DT = dual-task; Stroop_{single} = single-stimulus Stroop; $\text{Stroop}_{multiple}$ = multiple-stimuli Stroop; ML = medio-lateral; AP = antero-posterior; Stdev = standard deviation

[a]Significantly different than ST

[b]Significantly different than DT with Stroop_{single}

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